

Entry, Descent, and Landing Operations Analysis for the Genesis Re-Entry Capsule

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ENTRY, DESCENT, AND LANDING OPERATIONS ANALYSIS FOR THE GENESIS RE-ENTRY CAPSULE

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On September 8, 2004, the Genesis spacecraft returned to Earth after spending 29 months about the sun-Earth libration point collecting solar wind particles. Four hours prior to Earth arrival, the entry capsule containing the samples was released for entry and subsequent landing at the Utah Test and Training Range. This paper provides an overview of the entry, descent, and landing trajectory analysis that was performed during the Mission Operations Phase leading up to final approach to Earth. The operations effort accurately delivered the entry capsule to the desired landing site. The final landing location was 8.3 km from the target, and was well within the allowable landing area. Preliminary reconstruction analyses indicate that the actual entry trajectory was very close to the pre-entry prediction.

INTRODUCTION

Genesis, the fifth of NASA's Discovery class missions, was launched on August 8, 2001. It is the first mission to return samples from beyond the Earth-moon system. Genesis was inserted into a halo orbit about the sun-Earth libration point (L1) where it collected solar wind particles over a period of approximately 29 months. The solar wind particles were collected in collector arrays, which were exposed by opening the capsule (Fig. 1). The arrays faced the sun, and the particles were trapped in a silica-based material. The collector arrays were retracted at the end of the collection period and the capsule was closed. Reference 1 gives an overview of the Earth return trajectory strategy.

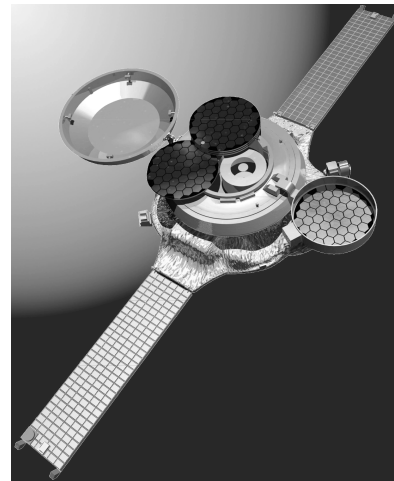


Figure 1. Genesis Spacecraft Sampling Configuration

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Upon Earth return on September 8, 2004, the entry capsule containing the solar wind samples was released from the main spacecraft, and descended through the Earth's atmosphere (decelerating with the aid of a parachute) for a mid-air recovery using a helicopter over the U.S. Air Force's Utah Test and Training Range (UTTR) in Northwest Utah. Unfortunately, due to a hardware malfunction during the descent, the signal to initiate parachute deployment failed and the capsule subsequently impacted the surface.

This paper provides an overview of the entry, descent, and landing (EDL) trajectory analysis that was performed during the Genesis Mission Operations Phase upon final approach to Earth. In addition, how the predicted landing location and the resulting overall 99 percentile footprint ellipse (obtained from a Monte Carlo analysis) changed over the final days and hours prior to entry is also presented. This analysis was required in order to substantiate the robustness of the capsule descent to assure that all entry mission requirements were satisfied prior to gaining authorization for capsule separation from the main spacecraft. Lastly, preliminary results from a reconstruction analysis for the Genesis entry is provided.

EDL Overview

The Genesis sample return capsule (SRC) is approximately 1.5 m in diameter. Its forebody is a blunted 60 deg half-angle sphere-cone. The afterbody is a bi-conic backshell with a first cone turning angle of 20 deg and a second cone turning angle of 61.6 deg (Fig. 2).

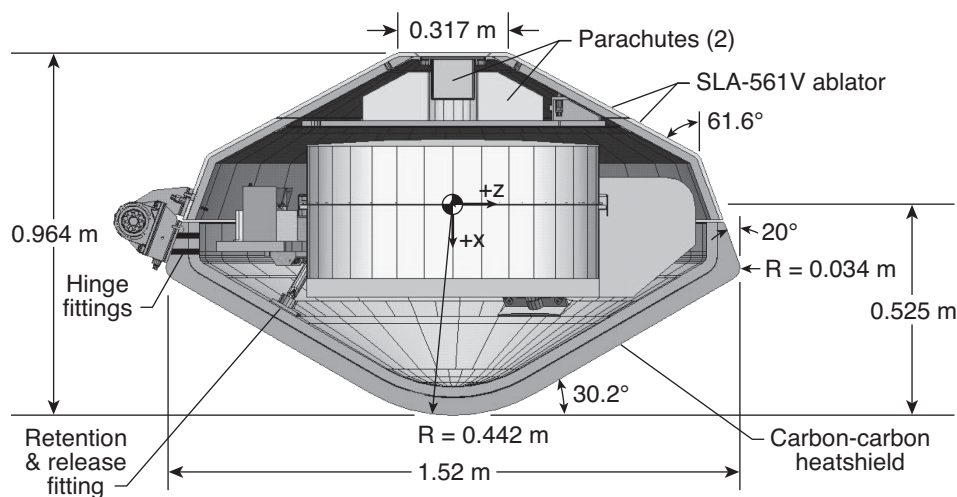


Figure 2. Genesis SRC Configuration

Figure 3 shows the nominal entry sequence, with the terminal descent phases highlighted. Four hours prior to entry, the 205.6 kg Genesis SRC was spun-up to 15 rpm and separated from the main spacecraft. The SRC has no active control system, so the spin-up is required to maintain its entry attitude (nominal 0 deg angle-of-attack) during coast. Throughout the atmospheric entry, the passive SRC relies solely on aerodynamic stability for performing a controlled descent through all aerodynamic flight regimes: free molecular,

hypersonic-transitional, hypersonic-continuum, supersonic, transonic, and subsonic. The SRC must possess sufficient aerodynamic stability to overcome the gyroscopic (spin) stiffness in order to minimize any angle-of-attack excursions during the severe heating environment. Additionally, this stability must persist through the transonic and subsonic regimes to maintain a controlled attitude at main parachute deployment. The inertial entry velocity and flight-path angle for Genesis were 11.04 km/s and -8.0 deg.

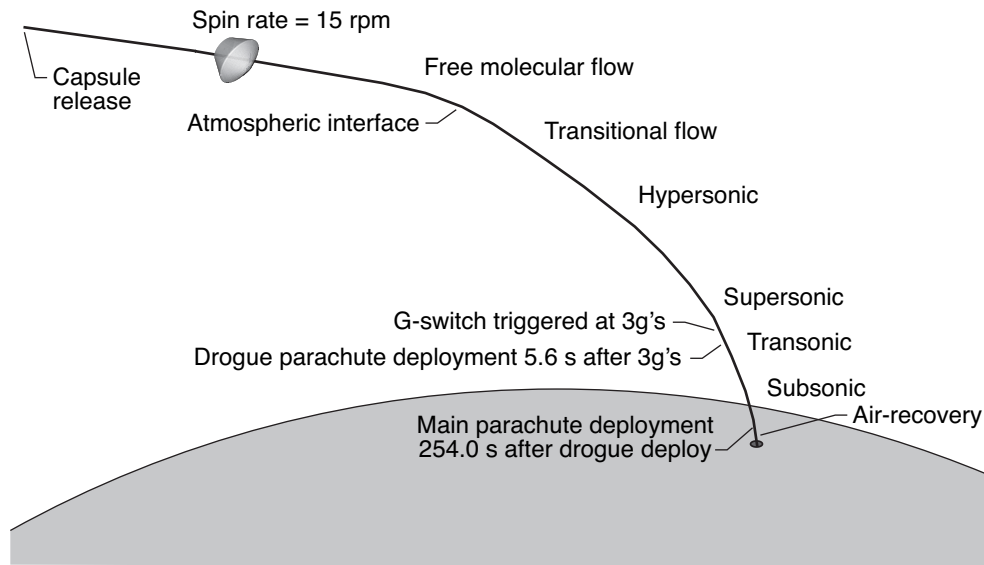


Figure 3. Nominal Genesis SRC Entry Sequence

Reference 2 provides an in-depth description on the development of the entry scenario; specifically, the use of the high spin rate and a supersonic drogue parachute. During descent, the entry profile utilizes a g-switch (i.e., gravity-switch) and two timers for deployment of the drogue and main parachutes. The g-switch is triggered after sensing 3 g's (on the decelerating side). At that point, the drogue timer is initiated. After 5.6 seconds, the drogue parachute is deployed (approximately Mach 1.8), and the main timer is initiated. After 254.0 seconds (approximately at 7.5 km), the main parachute is deployed. A helicopter air-recovery of the SRC was to occur at an altitude of approximately 2.45 km. This nominal entry sequence is sufficiently robust to accommodate off-nominal conditions during the descent as shown by the Monte Carlo dispersion analyses in Ref. 2.

The Genesis event timeline for final Earth approach is shown in Figure 4, which highlights the Trajectory Correction Maneuvers (TCM) that were baselined for attaining the proper entry conditions. Reference 1 provides an overview of the entire Earth return strategy showing all of the required TCMs. Prior to TCM-10, which occurred at entry (E) minus 10 days, the Genesis return trajectory was on a path that missed the Earth. Only after TCM-10 was successfully executed did the trajectory of the SRC become targeted at the Earth, with placement of the nominal landing location being in the western portion of UTTR.

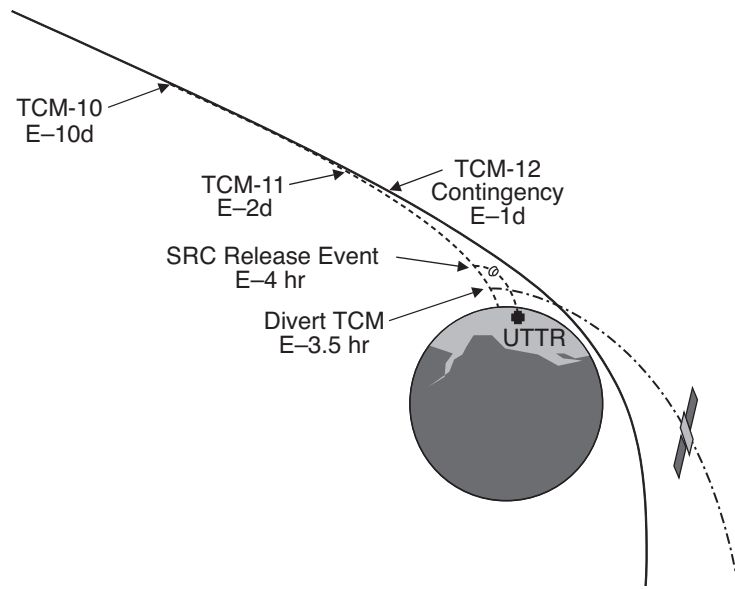


Figure 4. Genesis Final Earth Approach Event Timeline

Final targeting was accomplished with TCM-11 at E-2 days, which shifted the nominal landing location to the desired center of the UTTR. If TCM-11 had not executed or only partially executed, a contingency maneuver TCM-12 would have been implemented at E-1 day to achieve the final desired landing location. At E-4 hours, the SRC was separated from the main spacecraft, thus starting the EDL sequence illustrated in Fig. 3. At E-3.5 hours, a TCM was performed to divert the main spacecraft into an orbit ahead of the Earth.³ If TCM-10, 11, and 12 had all been unsuccessful, the capsule/main spacecraft would have flown by the Earth as depicted in Fig. 4. During Mission Operations, both TCM-10 and TCM-11 executed very successfully, as did the separation and divert maneuvers. As a result, the desired entry conditions were achieved with amazing accuracy.⁴

TRAJECTORY SIMULATION

Entry Trajectory Requirements and Constraints

The Genesis atmospheric entry trajectory is designed to fit within an envelope of derived requirements and physical constraints based upon the capsule hardware design. As such, for a successful landing, all entry requirements must be satisfied. Table 1 lists all the EDL requirements and their specific bounds. Monte Carlo dispersion analyses, described in subsequent sections, were performed during the Mission Operations Phase to assess the satisfaction of these requirements.²

Table 1: EDL Requirements and Constraints

Requirement	Limit
Entry Flight-Path Angle, deg	< 0.08
Entry Velocity, km/s	< 11.07
Entry Attitude, deg	< 10
Max Heat Rate, W/cm ²	< 510
Attitude at Max Heat Rate, deg	< 10
Max Heat Load, KJ/cm ²	< 16.6
Max Deceleration, Earth g	< 40
Drogue Chute Deployment Attitude, deg	< 30
Drogue Chute Deployment Mach Number	> 1.1 & < 2.3
Main Parachute Altitude, km	> 6.7
Landed Footprint, km	< 84

Monte Carlo Uncertainty Sources

During the entry, off-nominal conditions may arise that affect the descent profile. These off-nominal conditions can originate from numerous sources: capsule mass property measurement uncertainties; separation attitude and attitude rate uncertainties; limited knowledge of the flight-day atmospheric properties (density and winds); computational uncertainty with the aerodynamics; and uncertainties with parachute deployment. In the analysis, an attempt was made to conservatively quantify and model the degree of uncertainty in each mission parameter. For this entry, 41 potential uncertainties were identified.² Table 2 captures these uncertainty sources, respectively, along with their corresponding 3- σ variances. The subsequent sections describe in greater detail a few of the key uncertainty sources.

Table 2: Monte Carlo Analysis Variables

Variable	3-σ Variation	Distribution
Entry states	Based on covariance (See Ref. 4)	—
Mass, kg	± 0.25	Uniform
Radial center-of-gravity offset, mm	± 0.71	Uniform
Axial center-of-gravity, mm	± 0.71	Uniform
Moments of Inertia (Ixx, Iyy, Izz)	$\pm 5\%$, $\pm 5\%$, $\pm 5\%$	Uniform
Cross products (Ixy, Ixz, Iyz), kg-m ²	± 0.06 , ± 0.06 , ± 0.75	Uniform
Entry pitch and yaw attitude, deg	± 3.77 , ± 4.03	Gaussian
Entry pitch and yaw rates, deg/s	± 3.61 , ± 1.78	Gaussian
Entry roll rate, deg/s	± 6.04	Gaussian
Aerodynamic coefficients	See Ref. 2	—
Drogue Parachute C_D	$\pm 10\%$	Uniform
Main Parachute C_D	$\pm 10\%$	Uniform
G-switch acceleration trigger value	$\pm 10\%$	Uniform
Drogue parachute timer, s	± 0.05	Uniform
Main parachute timer, s	± 0.05	Uniform
Atmosphere	GRAM-95 model (See Ref. 5)	—

Entry Covariance

The original Genesis strategy for Earth approach was revised to maximize public safety in light of possible anomalies and contingencies, while still preserving the capability to meet the nominal entry requirements.¹ As a result, a series of maneuvers were performed to set up the approach and entry (see Ref. 1). Initial conditions at entry were obtained from orbit determination solutions performed by the Genesis Navigation Team. Reference 4 gives a description of the navigation process during the return phase and the determination of the final arrival conditions prior to entry. The navigation accuracy obtained for Genesis yielded extremely small state errors upon Earth arrival. The final orbit determination solution produced a $3\text{-}\sigma$ inertial entry flight-path angle error of ± 0.0274 deg.

Capsule/Cruise-Stage Separation

Based on the final main spacecraft and capsule mass properties, a statistical separation analysis was performed to predict separation attitude and attitude rates errors. The attitude errors predicted in pitch and yaw were ± 3.77 deg and ± 4.03 deg, respectively. The attitude pitch and yaw rates errors were ± 0.61 deg/s and ± 1.78 deg/s, respectively, and the roll rate error was ± 6.04 deg/s. These variations are used as inputs in the Monte Carlo analysis.

Atmosphere Model

The Earth atmosphere model utilized by Genesis for the entry trajectory design and analysis was the Global Reference Atmospheric Model - 1995 Version (GRAM-95).⁵ This model is an amalgam of three empirically based global data sets of the Earth that can produce an atmosphere profile as a function of altitude for a given date, time, and positional location about the Earth. GRAM-95 produces a representative atmosphere taking into account variations in diurnal, seasonal, and positional information for a given trajectory to produce nominal density, temperature, and pressure profiles and their statistical perturbations along the trajectory flight track. GRAM-95 is not a predictive model. A profile is generated based on historical data for a given time, season, and location.

Figure 5 shows samples of five randomly perturbed density profiles as a percentage of the nominal profile for the Genesis entry date of September 8, 2004 produced by the GRAM-95 model. Also, depicted are the upper and lower ($\pm 3\text{-}\sigma$) boundaries of the possible density variation. In addition, GRAM-95 can also produce nominal wind profiles and their statistical perturbations for the northward, eastward, and vertical wind components. Figures 6 and 7 show five randomly sampled wind profiles (for the Genesis entry date of September 8, 2004) for the northward and eastward wind components, respectively, along with their upper and lower ($\pm 3\text{-}\sigma$) boundaries. In the Monte Carlo analysis, an atmosphere profile (density and wind components) was randomly generated for each case having the characteristics shown in Figures 5-7.

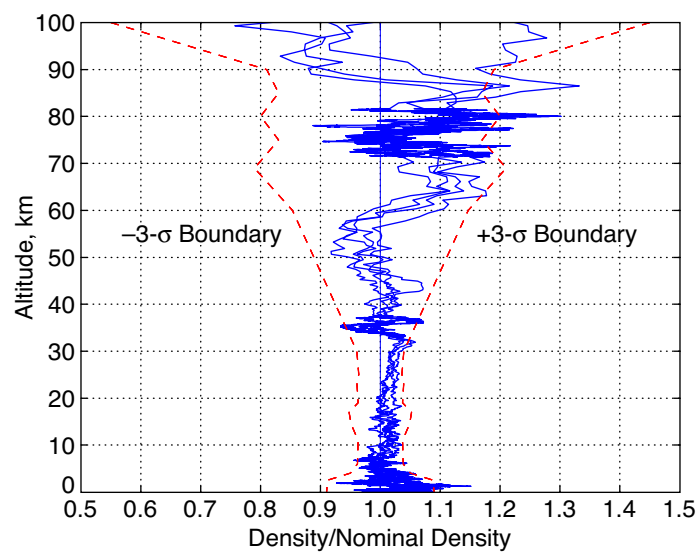


Figure 5. Density Variation from GRAM-95 Model

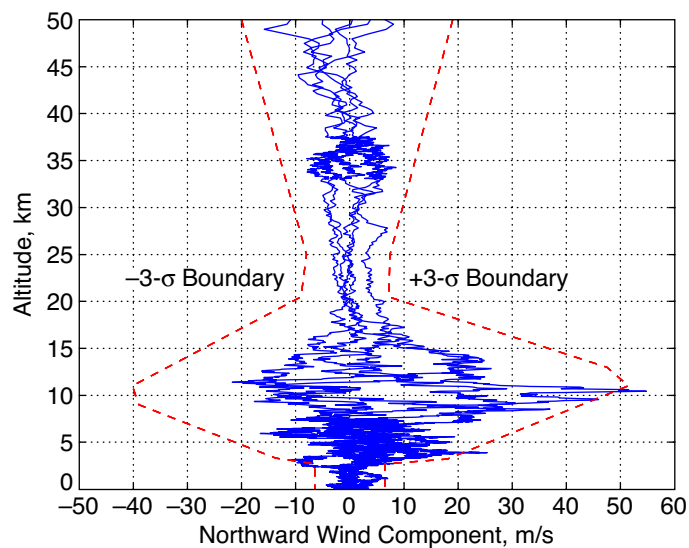


Figure 6. Northward Wind Component Variation from GRAM-95 Model

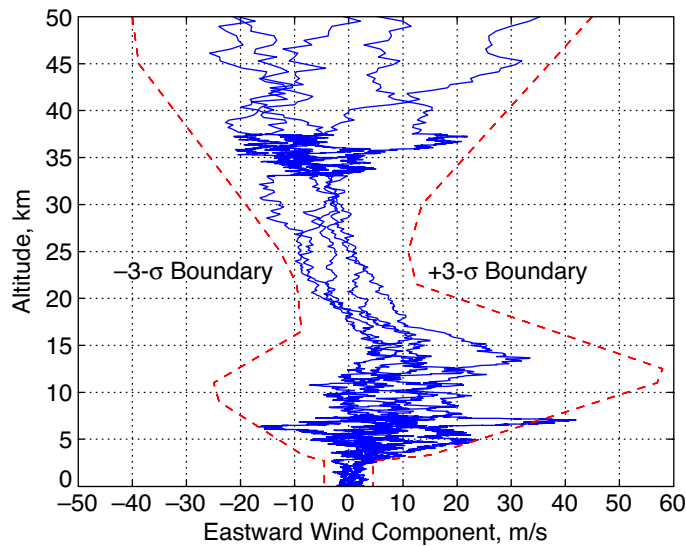


Figure 7. Eastward Wind Component Variation from GRAM-95 Model

Trajectory Analysis

Two trajectory propagation codes were utilized for the Genesis landing dispersion analyses: the Program to Optimize Simulated Trajectories (POST) program⁶ and the Atmospheric-Entry Powered Landing (AEPL) program.⁷ These codes were employed to obtain independent verification of the predicted nominal landing location and the overall size of the dispersed landing footprint ellipse to ensure public safety by landing within the UTTR boundaries.

The POST trajectory analysis was performed modeling six-degree-of-freedom (6DOF) dynamics, which included all forces and torques on the spacecraft, from atmospheric interface to drogue parachute deployment. During this portion of the entry, the full set of capsule aerodynamics and mass properties were incorporated into the simulation to accurately model the hypersonic descent. From drogue parachute deployment to landing, three-degree-of-freedom (3DOF) dynamics were used, in which only the drag force was modeled and was assumed to act opposite the wind-relative velocity vector. The POST trajectory simulation seamlessly transitions from 6DOF to 3DOF dynamics within a single continuous simulation.

The version of the AEPL program used for Genesis employed 3DOF analyses throughout. Since the Genesis entry was unguided and ballistic, the 3DOF results from AEPL agreed well with the POST 6DOF/3DOF simulation. The POST results were baselined as prime for the mission. In general, there was very good agreement between the two simulations.

Monte Carlo Dispersion Analysis

A Monte Carlo dispersion analysis is utilized to statistically assess the robustness of the entry to off-nominal conditions to assure that all EDL requirements and constraints are satisfied (see Table 1). All the input variables listed in Table 2 are randomly varied in the Monte Carlo dispersion analysis, along with their respective variance and distribution type. The analysis included uncertainties in the initial state vector, capsule mass properties (mass, center-of-gravity, inertia), initial attitude and attitude rates, aerodynamic coefficients, atmospheric density and winds, parachute drag, g-switch trigger value, and parachute deployment timers.

For the dispersion analysis, 3000 random cases were run for all the navigation orbit determination (OD) solutions that were computed⁴ at the various event times during the Mission Operations Phase. This analysis was performed to determine the appropriate magnitude and direction of TCM-10 and TCM-11 for proper targeting to UTTR. In addition, this analysis was used to assess the OD solution stability and to understand the movement of the nominal landing location and the variation in the 99 percentile footprint size within UTTR. This understanding was crucial in order to gain authorization for capsule separation and the subsequent entry. The size of the 99 percentile footprint ellipse obtained from the Monte Carlo dispersion analysis was used in a public safety analysis to certify that the risks of the Genesis capsule entry were acceptable.⁸

The Monte Carlo dispersion analysis was performed on all the Post-TCM10 OD solutions (OD139 through OD144). Figure 8 shows the corresponding results at landing. For clarity, only the results for three OD solutions are shown (OD139, OD141, and OD144), where their nominal landing locations (center points) and the 99 percentile footprint ellipses at UTTR are depicted. As previously stated, TCM-10 targets the nominal landing location towards the western portion of UTTR (approximately 55 km from the target). The target location selected for Genesis is near the center of UTTR having the coordinates 246.4667 deg East Longitude and 40.2 deg North Latitude.

Over the course of Post-TCM10 OD solutions, the nominal landing location is observed to drift as expected. The movement is first towards the Southeast between OD139 through OD141, before reversing back towards the Northwest between OD141 through OD144. The later OD solutions begin to stabilize as more tracking data was available due to the increased observation time. The landing locations for OD142 through OD144 are hard to differentiate, as they lie nearly on top of each other. The added benefit of stable OD solutions arising from the increased observation time is that a refinement in the footprint size can be obtained. For the Post-TCM10 OD solutions, the 99 percentile footprint ellipses decrease in size. The footprint size decreases from 69.7 km by 27.7 km for OD139 to 46.5 km by 27.1 km for OD141 to 37.1 km by 26.7 km for OD144.

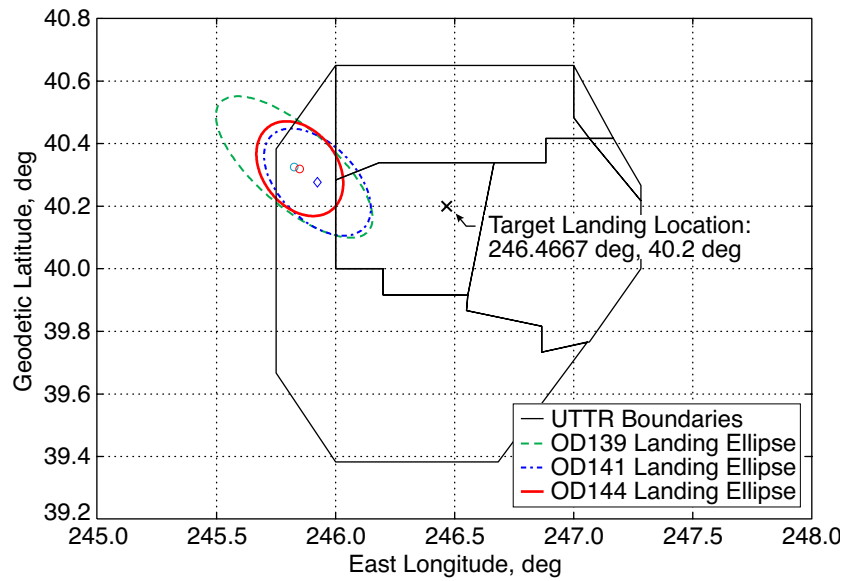


Figure 8. Landing Locations for Post-TCM10 OD Solutions

Similarly, Monte Carlo analyses were performed for all the Post-TCM11 OD solutions (OD150 through OD154). Figure 9 depicts the landing locations for a few of these OD solutions (OD150, OD152, and OD154). As seen, TCM11 moves the landing location to the center from the western portion of UTTR. All the OD solutions Post-TCM11 were extremely stable and produced nearly identical landing locations as observed in Fig. 9, where the 99 percentile landing ellipses lie nearly on top of each other. The results for OD154 showed that all the EDL requirements and constraints were well within their limits, and that

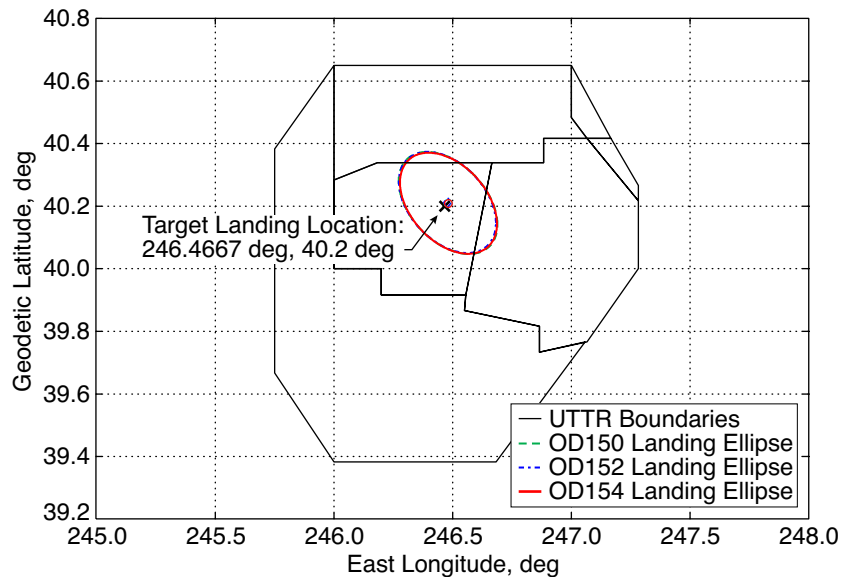


Figure 9. Landing Locations for Post-TCM11 OD Solutions

the final predicted nominal landing location was very close to the desired target (only 1.65 km away). The final overall 99 percentile landing ellipse was calculated to be 41.9 km by 21.1 km having an azimuth orientation angle of 137.2 deg (measured clockwise positive from North). Based on these OD154 results (which was the last OD solution available prior to entry), the authorization for capsule separation and subsequent entry was granted. Unfortunately, due to a hardware malfunction during the descent, the signal to initiate drogue parachute deployment failed and the capsule subsequently tumbled and impacted the surface. The final impact point was 8.3 km south of the desired target as shown in Fig. 10, which is well within the final OD154 pre-entry predicted 99 percentile landing ellipse.

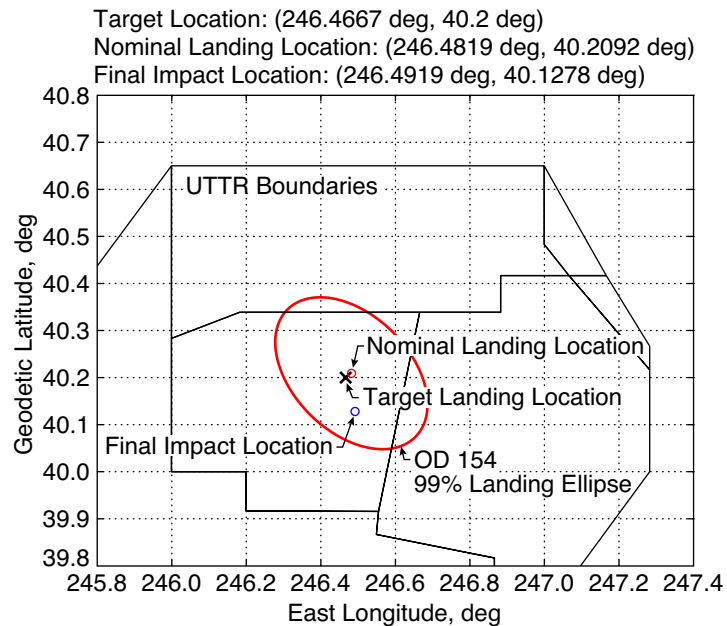


Figure 10. Final Capsule Landing Location

ENTRY RECONSTRUCTION

A preliminary flight reconstruction of the data shows that the Genesis entry was very close to the pre-entry predicted nominal profile. Unfortunately, there were no onboard sensors from which a traditional reconstruction could be performed. Hence, this preliminary reconstruction effort used the data sets that were available; namely, the final OD solution (OD154) and the UTTR radar tracking data, which locked onto the capsule during the descent.

With this data set, a best estimated trajectory is calculated by finding a multiplier on the atmospheric density in order to determine the density variation that is needed to match the UTTR tracking data. An 8.1 percent reduction in the atmospheric density from the nominal pre-entry predicted density profile generated by GRAM-95 produces an entry trajectory that matches the UTTR tracking data very well (latitude, longitude, altitude, and velocity). This

8.1 percent lower density profile is within the $-3\text{-}\sigma$ boundary predicted by GRAM-95 as observed in Fig. 5.

The maximum g loads obtained from the best estimated trajectory was 27.0 Earth g as compared to 27.2 Earth g calculated for the nominal pre-entry predicted trajectory. The $3\text{-}\sigma$ variation in the maximum g loads from the final pre-entry Monte Carlo analysis was ± 1.84 Earth g. Hence, the actual Genesis capsule entry was very close to the pre-entry predicted nominal, and well within the $3\text{-}\sigma$ dispersions. As a result, the peak heating rate experienced should also be very close to the nominal environment predicted during the design phase.

Since there was no on board sensor data, the capsule hypersonic entry attitude behavior cannot be determined. Therefore, the attitude during the entry must be inferred from observations of the recovered capsule forebody and afterbody heatshield material response. The observations of the forebody and afterbody heatshield show that the attitude during entry must have been very close to the pre-entry predictions. There is very little, if any, charring of the shoulder region or the afterbody Thermal Protection System material. This observation suggests that the capsule attitude must have been only a few degrees during the entry. The observations of the recovered heatshield corroborate the pre-entry attitude predictions and support the estimates of a small hypersonic angle-of-attack and the resulting heating rate and heat loads estimations.

Although, this reconstruction analysis is preliminary and still ongoing, an overall assertion can be made that the Genesis entry (trajectory and attitude behavior) was very close to the nominal pre-entry prediction. As a result, the design principles and methodologies utilized for the flight dynamics, aerodynamics, and aerothermodynamics analyses have been validated.

CONCLUSIONS

On September 8, 2004, the Genesis entry capsule containing the solar wind samples was released from the main spacecraft, and descended through the Earth's atmosphere. The navigation and the entry, descent, and landing trajectory analyses that were performed during the Mission Operations Phase upon final approach to Earth accurately delivered the entry capsule to the desired landing site. The capsule landed 8.3 km from the desired target, and was well within the allowable landing area at the Utah Test and Training Range. As a result, the process of targeting a capsule from deep space and accurately landing it on Earth was successfully demonstrated. Preliminary reconstruction analyses indicate that the actual entry trajectory was very close to the pre-entry prediction. As a result, the design principles and methodologies utilized for the entry flight dynamics, aerodynamics, and aerothermodynamics analyses were validated. This ability will be demonstrated again in January 2006 for the Stardust mission.

ACKNOWLEDGMENTS

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